MODELING THE PLUME FROM THE EXHALANT SIPHON OF THE ZEBRA MUSSEL (*DREISSENA POLYMORPHA*)

A Thesis

Presented in Partial Fulfillment of the Requirements for

Graduation with Distinction in the

College of Engineering of The Ohio State University

By

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ABSTRACT

The zebra mussel, *Dreissena polymorpha*, was first observed in the Great Lakes in 1988. The environmental and economic impacts of these mussels have become staggering. Zebra mussels eat phytoplankton living in the water column. Of special interest to scientists is the zebra mussel's rate of food consumption. Currently, there is some question about the height and trajectory of the excrement from the mussel -- information necessary for determining where in the water column nutrients are supplied to the phytoplankton. A single juvenile zebra mussel was mechanically modeled to scale. In still water, it produced a laminar and linear jet similar to plumes observed from live mussels. Time constraints prevented us from modeling the mussel in a current, but this is a good first step towards an accurate zebra mussel model.

To my mother and father --

for whom I will never be able to dedicate enough

ACKNOWLEDGMENTS

I wish to thank my advisor, Michael Foster, for his insight, his kind words of encouragement, his easygoing manner, his time, and his patience – all of which made this undertaking an enjoyable endeavor.

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I thank David Culver for helping me understand the workings of the zebra mussel and bringing a refreshing, non-engineering point of view to this project.

I am grateful to Ellen McDonald who guided me to this project, helped to locate a huge amount of mussel data, and provided many useful ideas for this experiment.

I would also like to thank Jennifer Peterson for dotting my i's, crossing my t's, and keeping me smiling through this entire process.

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TABLE OF CONTENTS

TABLE OF FIGURES

INTRODUCTION

The zebra mussel, *Dreissena polymorpha*, was first observed in North America in Lake St. Clair in 1988 (Riessen, *et al*, 1993). Analysis has led scientists to believe that it was introduced from the Black Sea Region to the Great Lakes in 1985 or 1986 (Carlton, 1993). Most likely, the mussel was transported from Europe in the ballast water of ships. The new species of mussel, having no natural enemies in the Great Lakes, flourished and began to affect the region on a huge economic and ecological scale.

The mussels can attach themselves to almost any substrata, such as rocks, boat hulls, and shells of other mussels. They tend to cluster together, thus producing enormous problems when they block water intake pipes (Figure 1) and machinery in power plants and water treatment centers (Kovalak, *et al*, 1993).

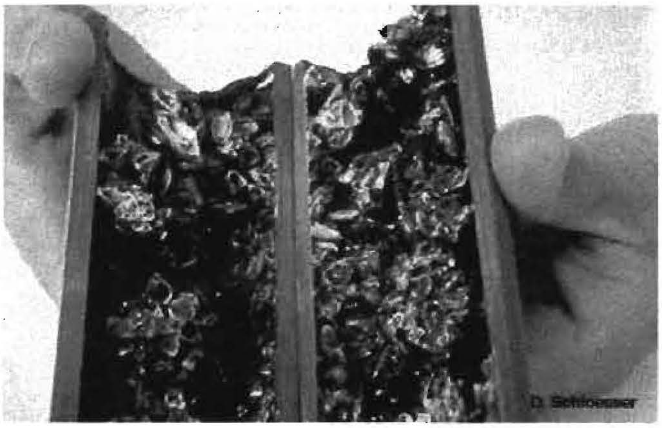


Figure 1 Zebra mussels clogging pipe (Michigan Sea Grant)

As one can imagine, zebra mussels have become a very expensive problem for the Great Lakes. "Experts predict that the recent invasion of zebra mussels… could cost manufacturing, power and municipal facilities more than $5 billion over the next decade" (Kebodeaux, 1995).

The invasion of the zebra mussels is not limited to the business of men, it is also affecting the leisure of men. Washington State's Department of Fish and Wildlife is now requiring the decontamination of all recreational equipment used for tournament fishing in any waters east of the Continental Divide (Zebra Mussel Update, 1997). This decontamination process requires paperwork and a rather involved cleaning process.

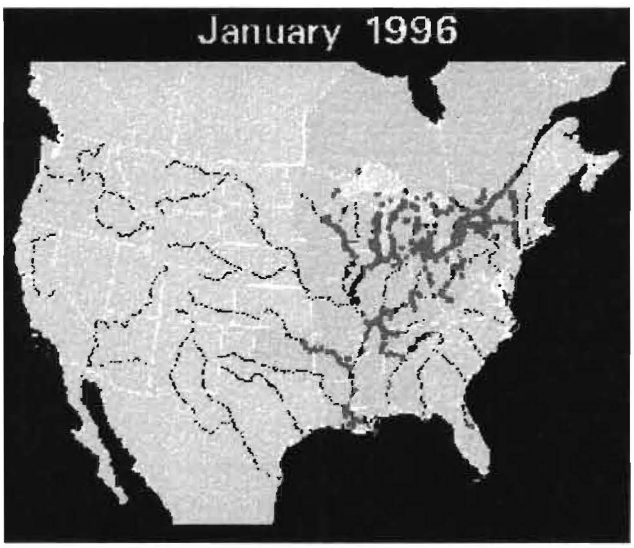


Figure 2 Zebra mussel distribution as of January 1996 (Zebra Mussel Update)

All over the country, wildlife and marine officials are asking outdoorsmen to be on the lookout for zebra mussels. It is predicted that *D. polymorpha* will be a conspicuous and dominant animal in the coming decades, spreading widely into estuaries (e.g., nontidal lagoons) and brackish lakes, such as those of the Dakotas and Canadian Prairie provinces (Strayer, et al., 1993). It appears that the mussel spreading is greater than what was first predicted (Figure 2). In fact, zebra mussels were found in late July 1995 at Alum Creek Reservoir near Columbus, Ohio, by the U.S. Army Corps of Engineers (Zebra Mussel Update, 1995). The mussel's impact on the Great Lakes has been enormous; therefore, it is important to study them as much as possible so that we may better deal with them as they propagate further into North America.

A large part of understanding the mussel is understanding and analyzing its biological processes. Zebra mussels eat phytoplankton that live in the water column with the mussel. Of special interest to scientists is the zebra mussel's rate of food consumption, which is important because only a certain number of mussels can survive on a given amount of food available in the environment. This issue is complicated by the fact that *D. polymorpha* excrement contains nitrogen and phosphates – nutrients needed for phytoplankton growth. Thus, it is somewhat circular: *D. polymorpha* eat the phytoplankton and then excretes nutrients, helping to feed the very phytoplankton it preys upon. How then can food consumption rate and food availability be accurately predicted? The answer begins by looking at the biology of *D. polymorpha.*

The digestive system of *D. polymorpha* interacts with the environment primarily through two siphons (Figure 3). The inhalant siphon has a relatively large opening surrounded by a crown of 80-100 tentacles arranged in two cycles. The exhalant siphon is conical with a posterodorsally directed opening smaller than that of the inhalant and lacking tentacles (Morton, 1993). Biologists and zoologists are able to examine the animals to determine the internal processes (i.e., volume

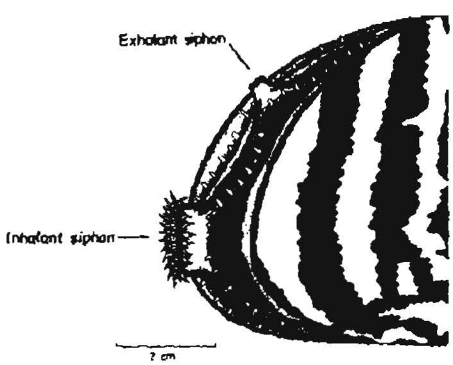


Figure 3 Zebra mussle siphons (Morton)

flow, excrement composition). The problem for animal scientists comes with the need to model the interaction of the inhalant and exhalant with the environment – a fluid mechanics problem.

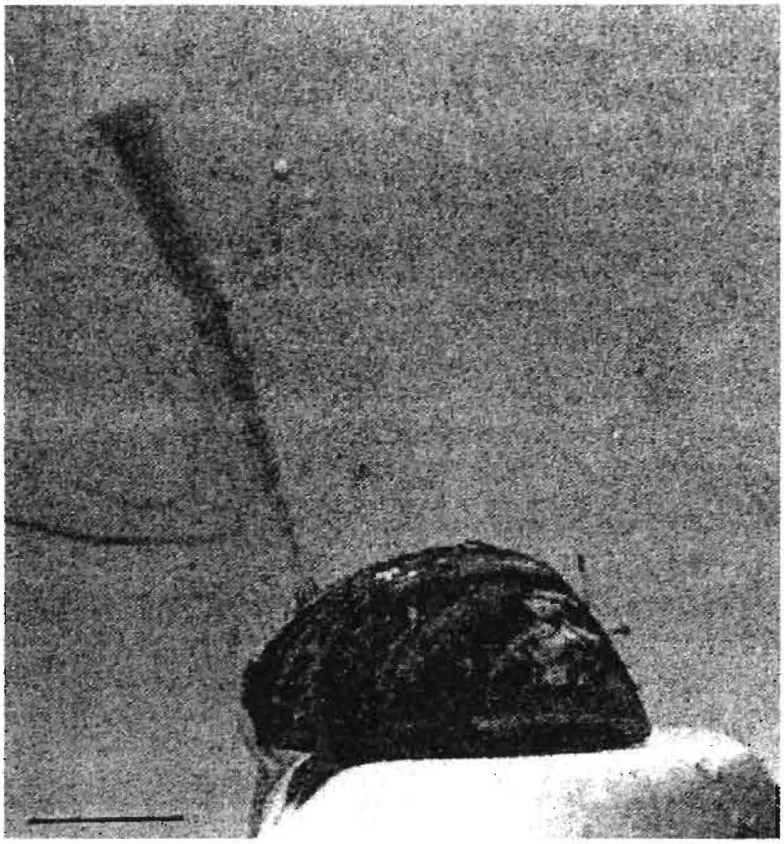


Figure 4 Linear and laminar exhalation of die from a live zebra mussel (Bunt, *et al*, 1992)

Currently, there is some question about the height and trajectory of the mussel's exhalant plume. The plume has been observed to have a linear and laminar flow path (Figure 4) in still water (Bunt, *et al*, 1992). A linear, laminar flow is a flow where the fluid is "observed to move in a well defined straight path, indicating that the fluid moved in parallel layers with no macroscopic mixing motion across the layers" (Kundu, 1990). Also of note in Figure 4 is the ring vortex structure at the head of the plume.

Plume information is necessary for determining where in the water column nutrients are supplied to the phytoplankton by the exhalant siphon's excrement. This knowledge will help to model phytoplankton densities in food consumption rate experiments and calculations.

OBJECTIVE

To model the plume from the exhalant siphon of a single zebra mussel

EXPERIMENTAL CONSIDERATIONS

Live animals will not be used in the experiment -- a conclusion reached for three reasons. First, modeling live animals increases experimental variability. All zebra mussels are slightly different, so accurate experimental reproducibility from day to day would be impossible with live animals. Second, economically and ecologically it is more feasible to model the mussel than to keep a stock of live mussels. As stated before, zebra mussels are very prolific and spread easily into water supplies. Keeping a tank or two of mussels would be expensive, and taking all necessary precautions in handling the

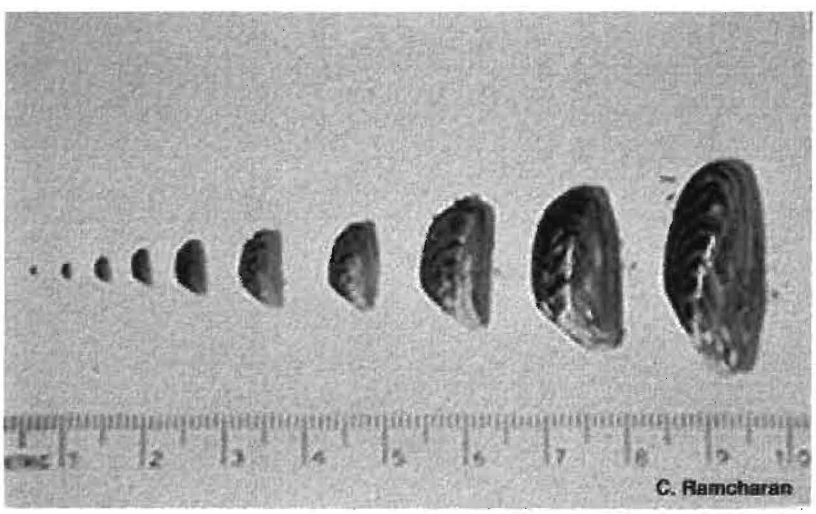


Figure 5 Ten zebra mussels ranging in size from pinhead size to 3 cm (Ramcharan)

mussels and cleaning the experimental facilities would be even more expensive. There is also significant paperwork inherent in the transport and handling of zebra mussels. Third, because of the average mussel's size (Figure 5), and since the only objective is to study the plume of a single mussel, experimentation will be much easier and more reliable if a mechanical or computer model is developed.

Figure 6 Colony of zebra mussels filtering (Ontario Ministry of Natural Resources)

As noted, *D. polymorpha* tend to grow in large clumps; therefore, not all of them have the same directional orientation (Figure 6). After discussion a with faculty member from the zoology department, we decided to model one mussel – not try to build a colony (Culver, 1996).

BACKGROUND

A similar study has been undertaken by Monismith, *et al,* at the Environmental Fluid Mechanics Laboratory of Stanford University. That study focused on the hydrodynamics of bivalve siphonal currents of clams, and also used mechanically modeled animals (Monismith, *et al*, 1990). The clams modeled ranged in length from 8 to 60 mm. The largest zebra mussels are typically less than 30 mm in length; the average adult mussel is between 10 to 20 mm (Mackie, 1993). The Stanford study will act as a good comparison for the accuracy of my findings.

The actual mussel modeling will be based on a 1992 study by Bunt, *et al,* at the University of Toronto. That study looked at the pumping rates and projected filtering impacts of juvenile mussels. It is noted in the study that small-bodied (2-11mm), juvenile mussels comprise up to 90% of the individuals in the reefs of Lake Erie (Figure 7). The study found that shell length could be correlated with less readily quantifiable aspects of *D. polymorpha*, such as

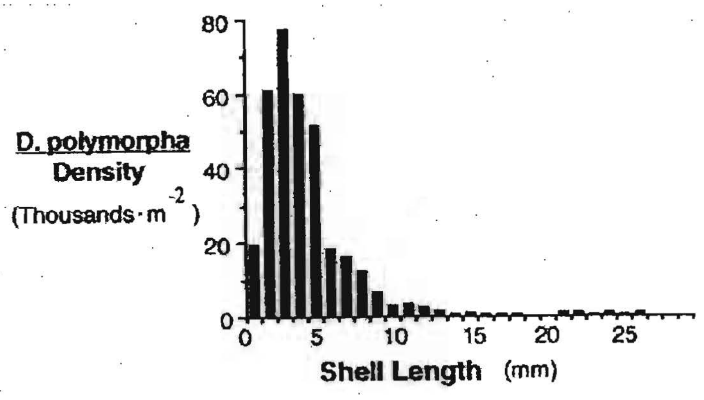


Figure 7 Mean size-frequency distribution of zebra mussel (Bunt, *et al*, 1992)

pumping rates, exhalant siphon surface area (Figure 8), and exhalant plume velocity. Using this correlation, Bunt's data provides a reasonable method for obtaining dimensions for creating an artificial mussel.

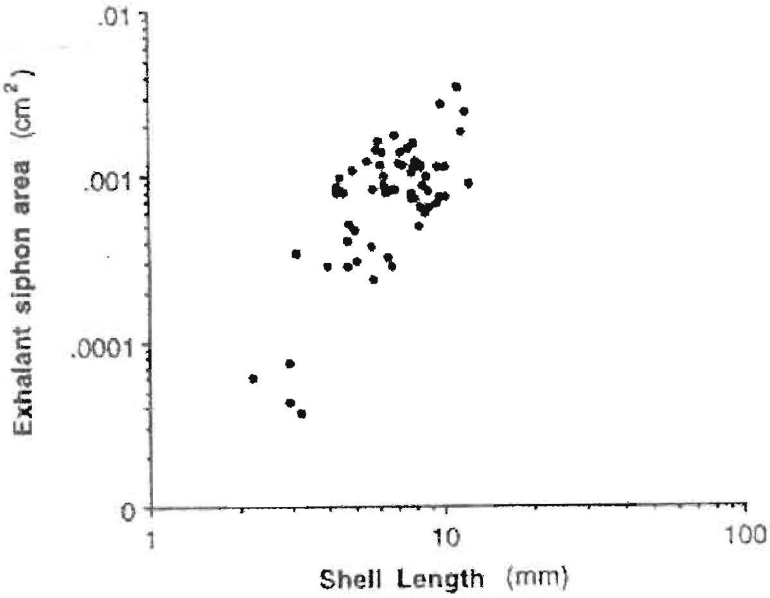


Figure 8 Exhalant siphon aperture surface area as a function of shell length (Bunt, *et al*, 1992)

The height and trajectory of the exhalant siphon is affected by a boundary layer that forms at the bottom of bodies of water – the benthic boundary layer. Boundary layers form because the fluid velocity is zero at the bottom, but some distance above the surface, the fluid is driven by wind and heating. Zebra mussels squirt their excrement into this benthic

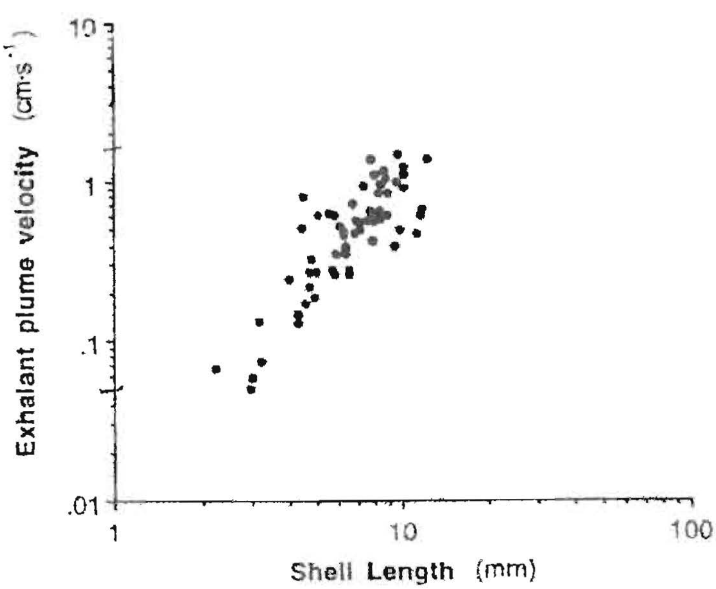


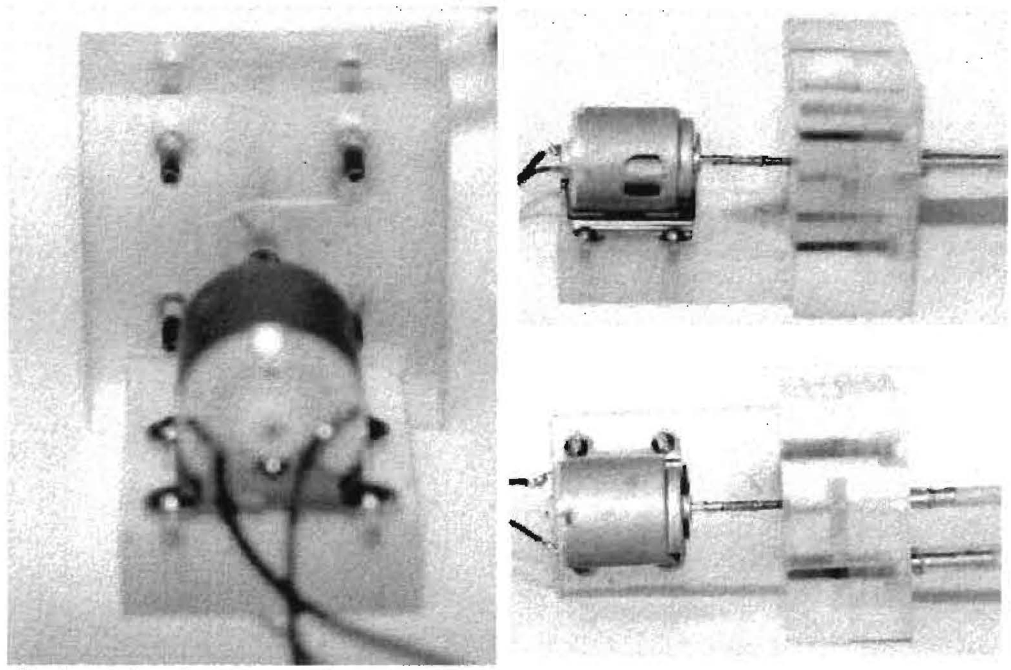
Figure 9 Exhalant plume velocity as a function of shell length (Bunt, *et al*, 1992)

boundary layer. Thus, to accurately model the height and trajectory from the exhalant siphon, one must model both the mussel siphon and the boundary layer.

The Bunt, *et al,* 1992 study was performed on live mussels in still water. In order to obtain a viable model, the still water case will be modeled and the results compared to the juvenile mussel findings. After the mussel model is completed, the modeling of the benthic boundary layer can commence.

EXPERIMENTAL APPARATUS

The heart of the artificial mussel is the centrifugal pump designed by Dr. Joseph Haritonidis (Figure 10). The water is circulated through the pump using an



(Clockwise from left) Rear, side, and top views of pump.

Figure 10 Mussel pump used in experimentation

impeller driven by a small DC motor. The motor is given a constant supply of power through a variable 15-volt DC power supply. The variability of the power supply allows the pump to run at many different flow rates; therefore, the pump is not limited to one siphon size. A detailed drawing of the pump is included in the appendix.

The impeller shaft was made from a 0.81-inch diameter steel drill bit. The blade of the impeller was made from a thin sheet of brass and is approximately 0.5-inches long and 0.9-inches tall. The two pieces of the impeller were soldered together.

The pump housing is made from two 0.5-inch thick blocks of plexiglass. The two blocks are held together by four screws. The front block has two holes drilled through it -- one acting as the flow input the other as the output. The back block contains the pump chamber. The chamber is made from a 0.5-inch diameter hole. A 0.1-inch by 1/8-inch channel was drilled in the top of the chamber, parallel to the top of the block. When the pump is running, water enters the center of the chamber, then the impeller pushes the water through the channel. The channel and hole are 0.1-inch deep. In the center of the chamber hole is a 0.81-inch diameter hole extending through the block. This is where the impeller shaft is placed and the impeller can then spin freely in the chamber.

The impeller shaft is connected to the motor's drive shaft by a spring. The mobility of the spring allows the impeller a certain amount of freedom to move within the confines of the chamber. The motor and pump are both held in place by being affixed to a plexiglass base.

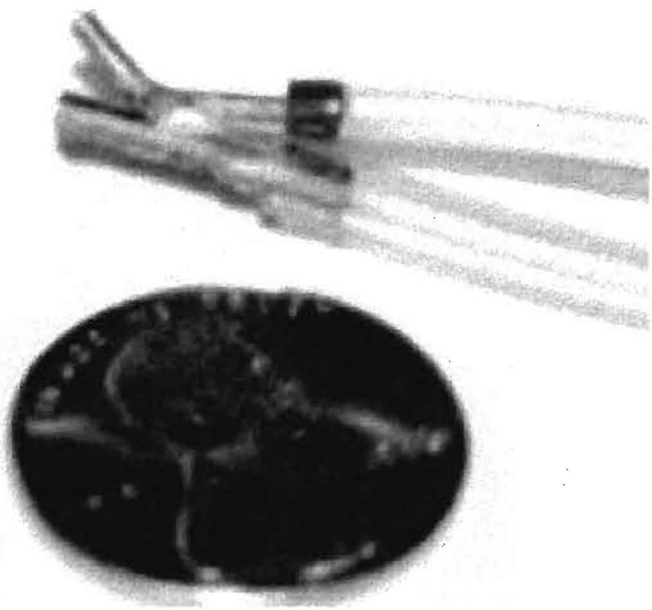


Figure 11 Model siphons

The pump is connected to the siphons via plastic tubing. The original siphon itself was made from plastic tubing, but there were problems with having the tubing hold the geometry of the mussel. Instead, metal siphons were made from stainless steel tubing (Figure 11). The inhalant siphon has a diameter of 55/1000-inch. The exhalant siphon has a diameter of 33/1000-inch. The angle between the two siphons is approximately forty degrees. The siphons are welded to a small brass base so that the siphon apparatus can sit on the bottom of a tank of water.

Flow visualization was performed by injecting a small amount of red food coloring or blue ink into the flow. This was done two different ways. The first method involved a small metal tube fitted with plastic tubing. The metal tube was placed in front of the inhalant siphon on the brass plate. Die was then injected into the plastic tubing with a syringe until a few drops of die were forced onto the plate. The inhalant siphon then took in the die and sent it through the pump. The second method involved injecting die directly into the plastic tubing that carried the exhalant flow. The injection method created a darker flow; however, the flow streamlines from the siphons could be viewed easily with either method.

The experiment was performed in a 14.5" x 9.5" x 10" plexiglass tank filled with tap water. The pump sat outside the tank on a small platform. The siphons and die tube were adhered to the tank using electrical tape.

We performed the experiment with a plume velocity of approximately 1cm/s. Using the exhalant diameter as the characteristic length, and the kinematic viscosity of water being on the order of 1×10^{-6} m^2/s, the Reynolds number is approximately 8. This low Reynolds number places the model well within the fluid dynamics realm where one expects to observe laminar jets -- an exact solution for the Navier Stokes equations for a laminar jet exists for arbitrary Reynolds numbers (Landau and Lifshitz, 1966).

We also began to construct a simple mathematical model of a flow field, superposing a laminar jet with a sink to represent the plume and inhalant. The original intent was that the study be exclusively experimental, but when difficulties in the mechanical modeling arose, we made an effort to explore the problem from a theoretical point of view. Unfortunately, the time remaining in the project precluded a thorough computational approach that would be required for modeling. Computer modeling remains an area in which some results could be gained with relative ease.

RESULTS AND DISCUSSION

Using the red die and ink for flow visualization, the exhalant plume created in still water was viewed to be linear and laminar as expected (Figure 12). The plume remained largely linear until the velocity of the plume was low enough that the

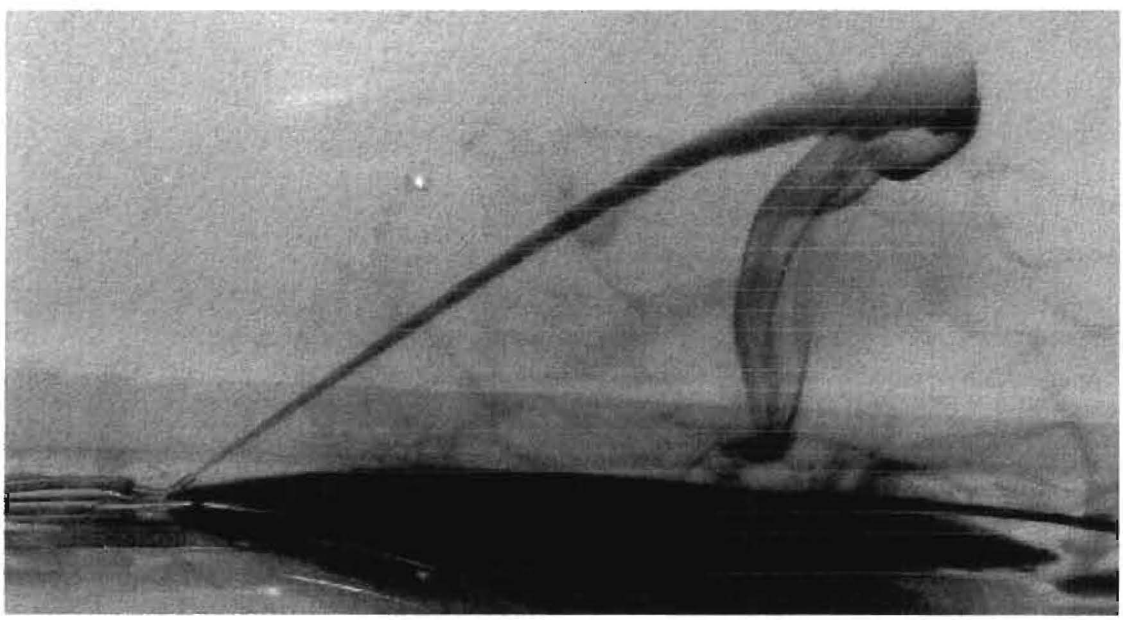


Figure 12 Linear, laminar plume from model mussel

particulates of die would begin to fall, as seen in Figure 12. When the die was diluted enough, the plume could be seen moving linearly a large distance from the siphon (Figure 13). This linearity is consistent with theory for a laminar jet in a low Reynolds number flow.

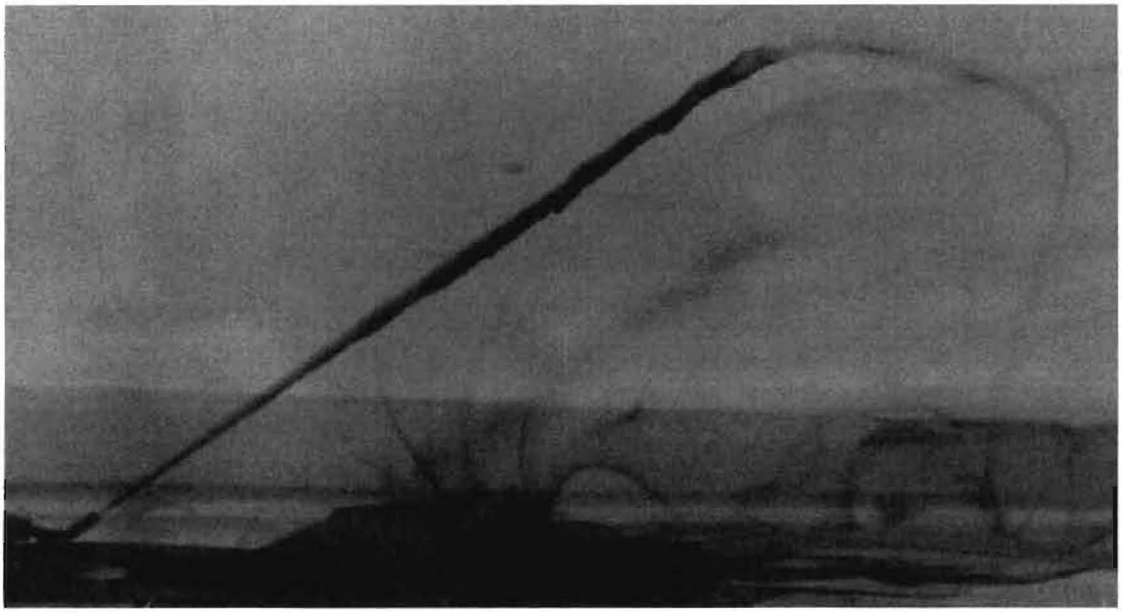


Figure 13 Plume highlighted with slightly diluted die

The linearity and laminar nature of the plume makes biological sense. The plume is waste from the mussel – it wants to get the waste away from its inhalant siphon. The most natural way to do this would be a linear and laminar jet. A

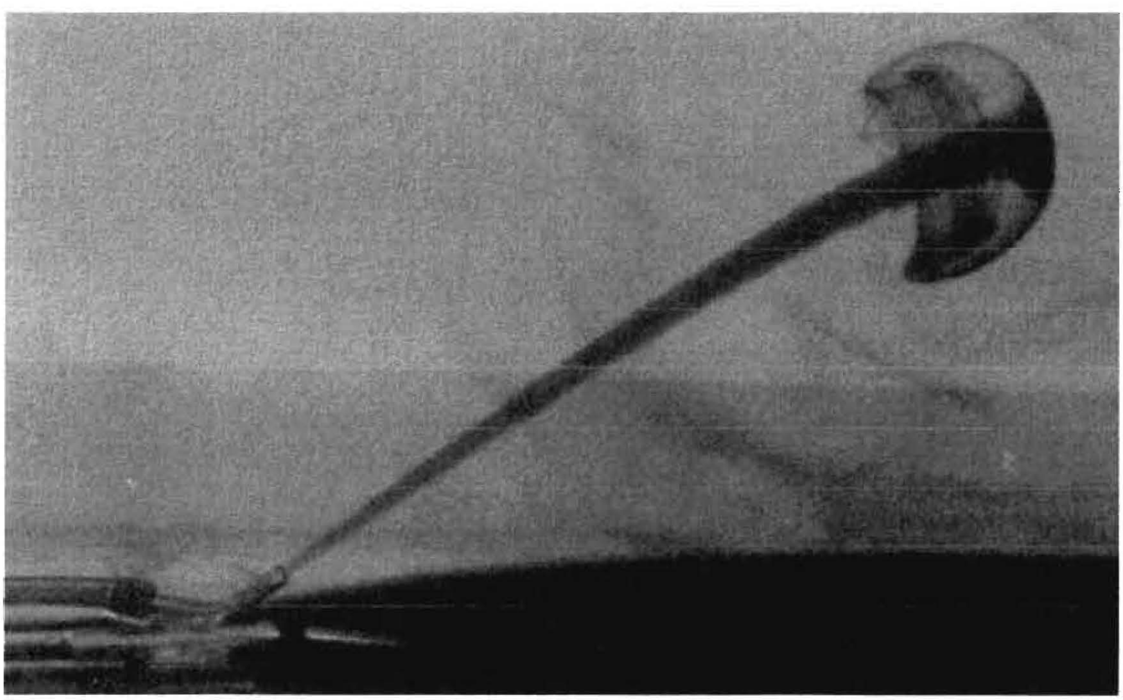


Figure 14 Model plume starting vortex

turbulent jet would cause a mixing and churning of the plume close to the mussel, which increase the likelihood that the mussel would have to inhale its excrement.

A starting vortex was often viewed at the starting of the pump (Figure 14). Biologically, any pulsing of the plume by the mussel would create ring vortex structures. These structures entrain external fluid and would cause mixing with the surrounding fluid rather than just simple penetration by the jet. Additionally, many vortices were also seen at the end of the plume. These vortices are expected fluid phenomena. At the end of the plume, the flow's velocity was very slow and the plume seemed to dissipate very rapidly.

As stated earlier, it was expected that the streamlines of the flow would be observed to exit at the exhalant siphon and then loop back around into the inhalant siphon. This expected pattern never materialized. The experiments seemed to support the idea that if the tank were not present, the streamlines would not return to the inhalant siphon. The plume particles would be carried away from the mussel. Additionally, given the low exit velocity of the plume (less than 1-cm/sec), it would quickly die out in most natural environments, where velocities are generally between 3 to 5-cm/sec. In a colony of mussels, these currents make it almost impossible that the fluid expelled by one mussel would return to that same mussel in a streamline. The plume will be taken away from the mussel in the current, possibly taken up downstream by another mussel in the colony.

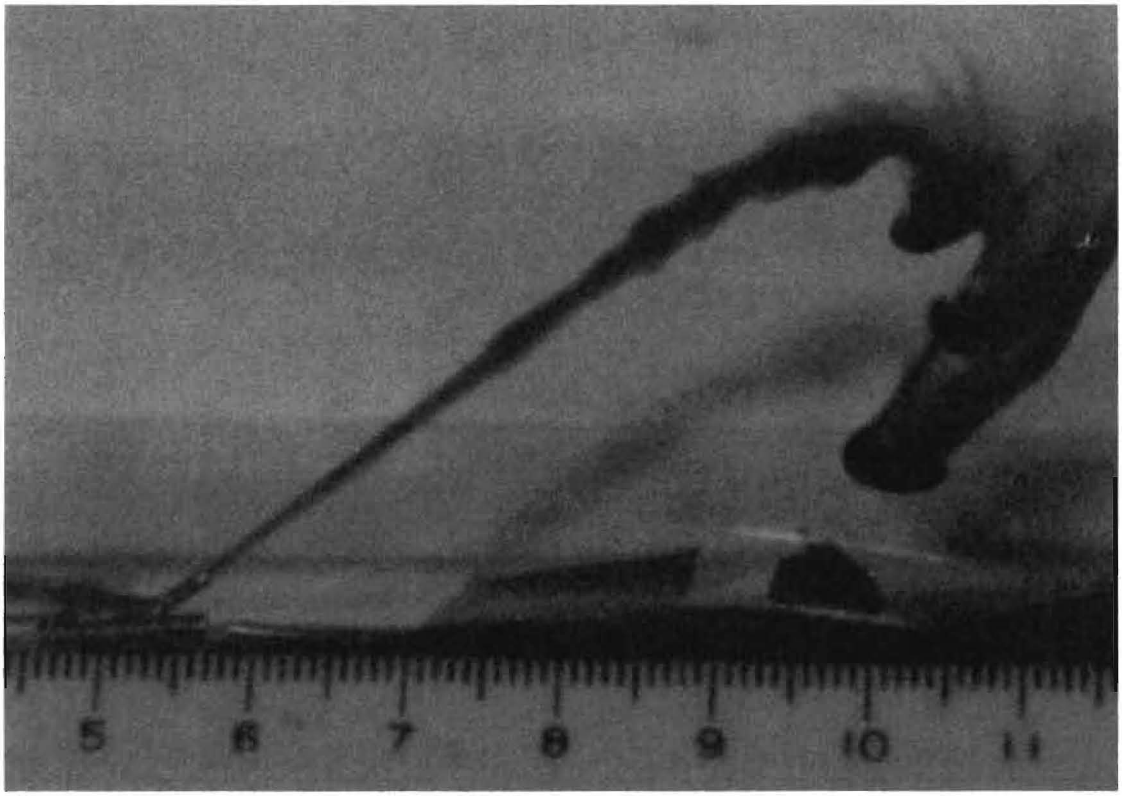


Figure 15 Plume falling due to die density

The die and ink used for visualization caused problems for the flow analysis (Figure 15). The densities of both were too high, so at the slow exit velocities needed for proper modeling, the plume showed two adverse characteristics. The first is that the plume quickly started falling, as seen in Figure 15. Also of note is the large pool of excess die that collected at the bottom of the tank, seen in Figure 12.

The second adverse characteristic is that the bottom edge of the plume would become jagged (Figure 16). At first, we thought that this instability might be one introduced by the motor. It is also possible that this is a surface tension interaction between the plume and the water. When introducing a jet of fluid such as the plume, into another fluid, the surface tension causes the plume fluid to want to assume a spherical shape. The jagged appearance of the bottom of the jet might be the die starting to ball up due to the surface tension interaction.

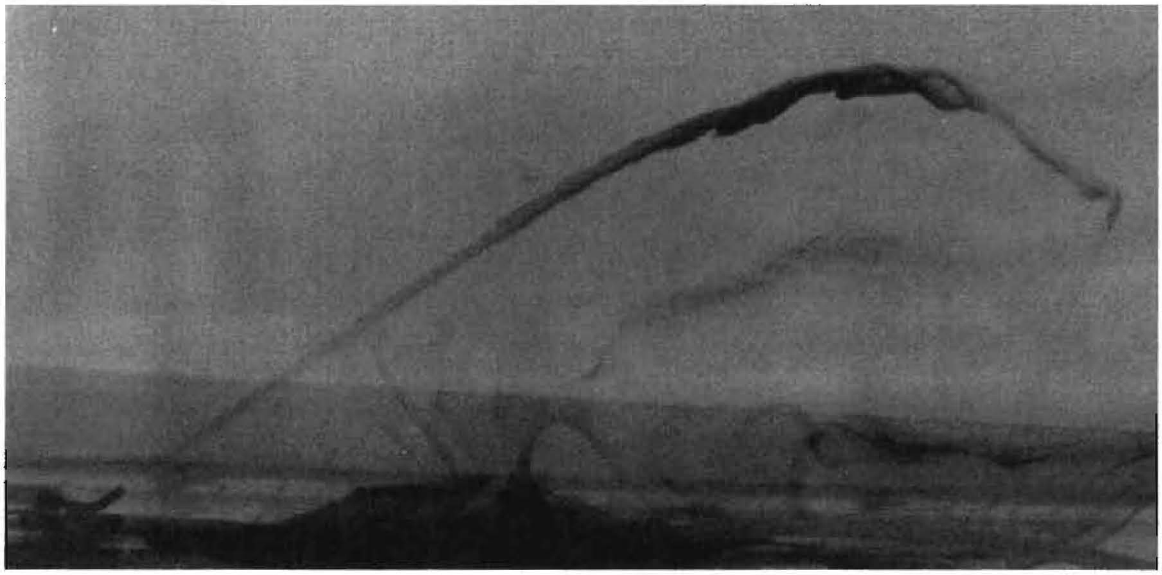


Figure 16 Jagged bottom edge of plume due to surface tension effects

CONCLUSIONS

This is a good start in the process of modeling the exhalant plume of the zebra mussel. During the course of the experiment, the following were accomplished:

- We successfully designed and produced a working, mechanical, scale model of a single juvenile zebra mussel.
- The plume created by the modeled mussel was linear and laminar for low exhalant velocities. This modeled plume also displayed observed natural plume characteristics, such as a starting ring vortex.
- Plume visualization displayed the weakness of the flow, indicating that in a current, the plume would rapidly dissipate and be carried away from the mussel inhalant.

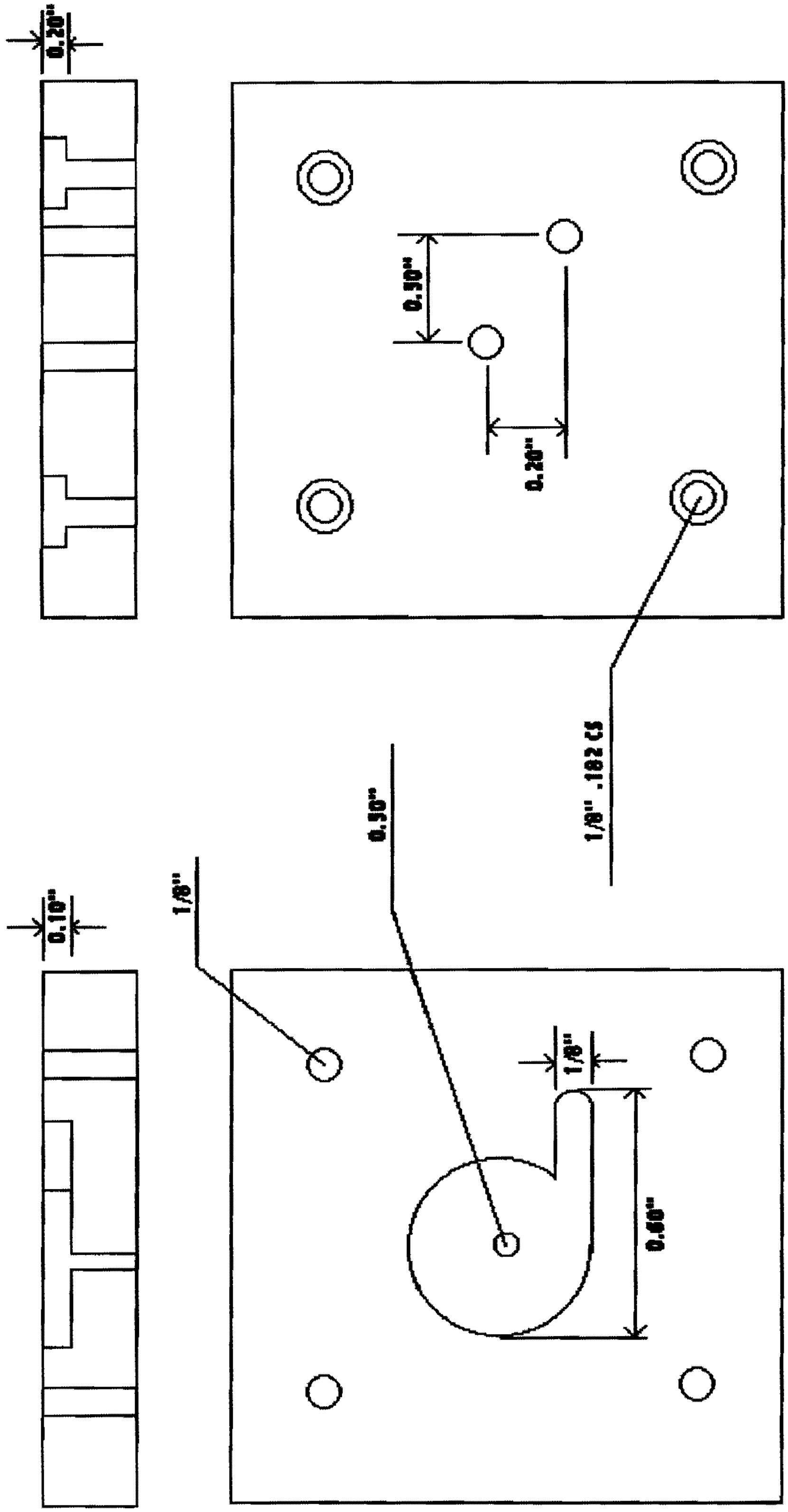
In future plume modeling research, the following issues need to be addressed:

- Visualization of the plume flow -- More care ought to be taken in the selection of a die. Care should be taken to attempt matching the density of the die to the actual exhalant density of the mussel. A method for injecting a consistent amount of die into the system might also be helpful if one is trying to focus upon where the plume particulates come to rest. Hopefully these steps would eliminate some of the problems we had with the die and ink we used for flow visualization.

- Measurement of the exhalant velocity -- The variability of the power supply is convenient for producing a variety of exhalant velocities; however, since we were in the early stages of modeling, we did not have an accurate way to determine the plume velocity. We suspect that a high-resolution video camera will have to be used to get an accurate plume velocity measurement.
- Modeling the benthic boundary layer -- The modeled mussel ought to be eventually placed in a flume and run at different current velocities to investigate the effects of the benthic boundary layer on the height and trajectory of the flow.
- Computer modeling -- If one can come up with a good three-dimensional model of a single mussel, it would be possible to develop a model of an entire bed of mussels. Ultimately, this would be of more use to biologists and zoologists than a model of a single mussel. Modeling a colony of mussels would give a more realistic determination of the mussels' effect on the water column. This would yield a far better estimate of the effects of the zebra mussel on the ecology and economy of North America.

APPENDIX

Pump Schematics



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